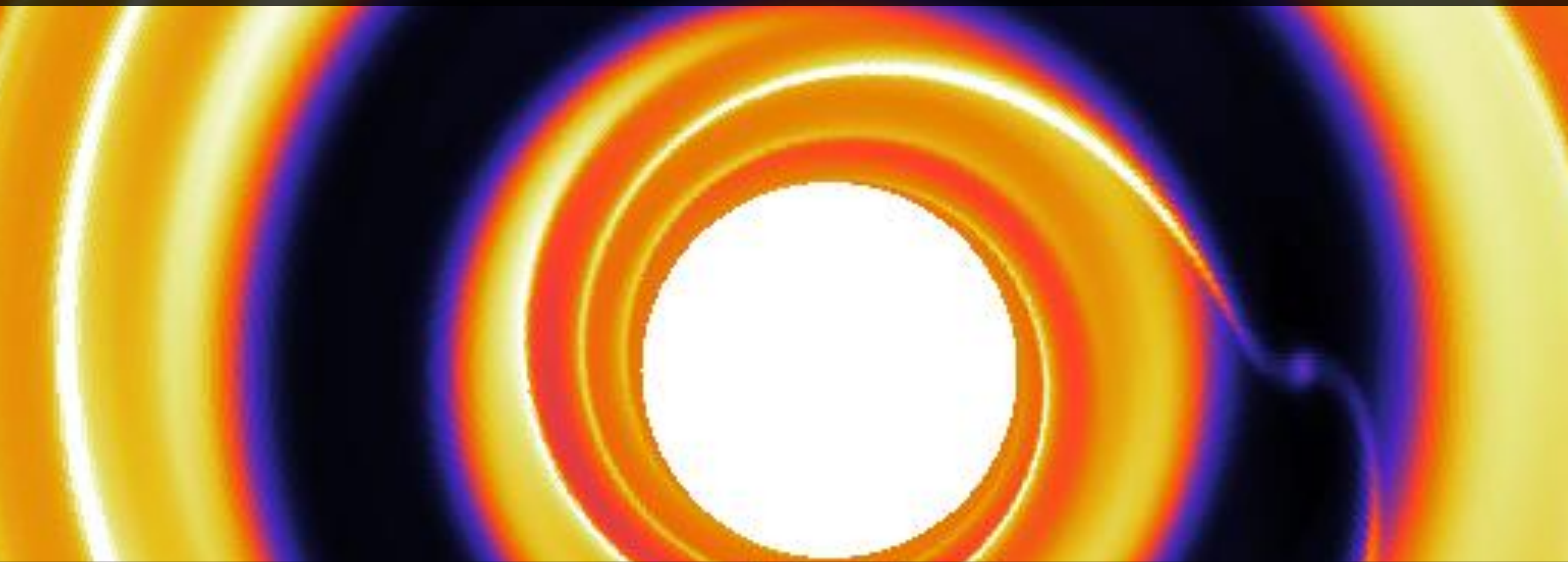
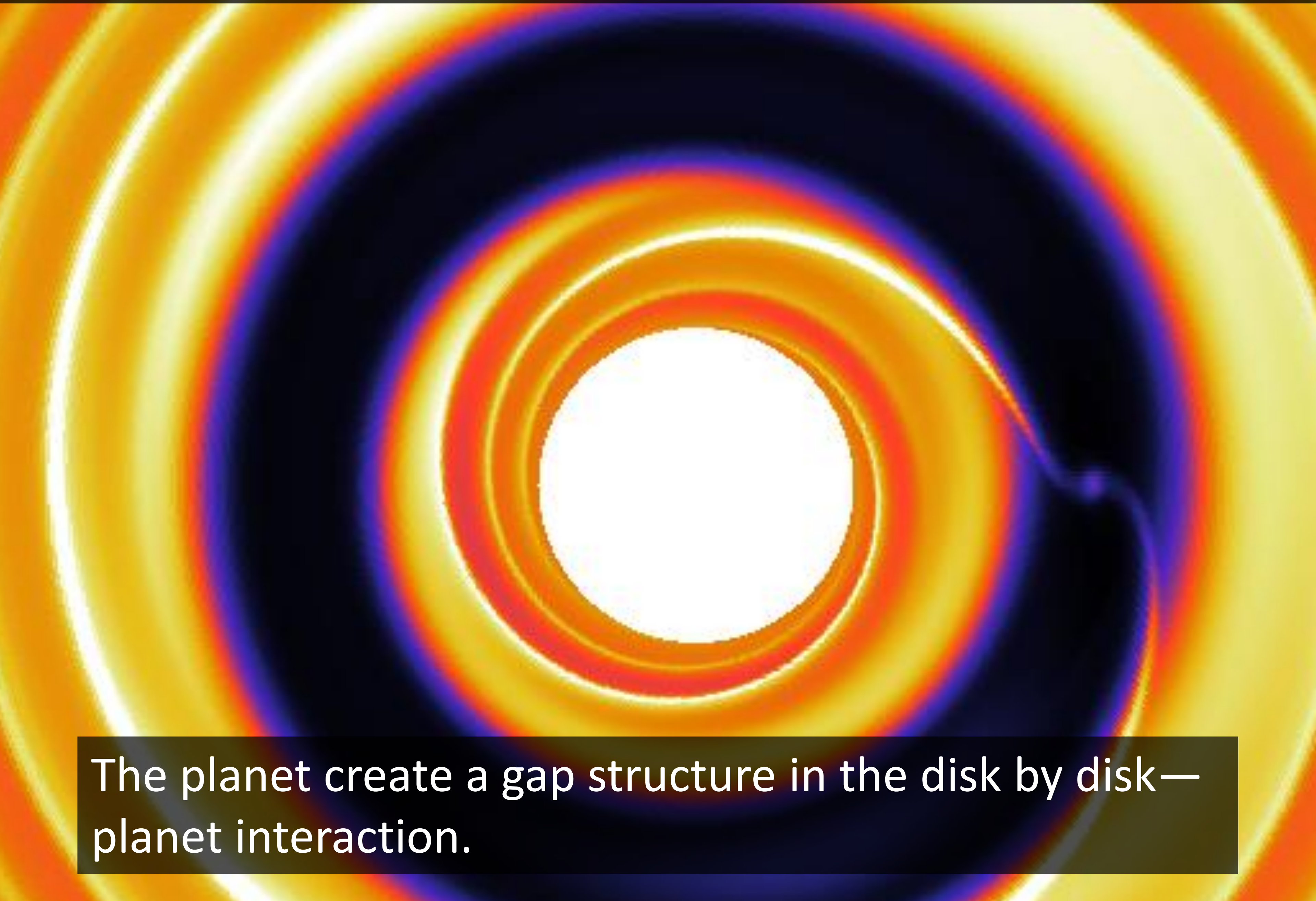
How to identify the mass of the planet within the gap in the protoplanetary disk from observation



Kazuhiro Kanagawa (University of Szczecin, Poland)

Takayuki Muto (Kogakuin Univ.), Hidekazu Tanaka (Tohoku Univ.),
Takayuki Tanigawa (NIT, Ichinoseki College),
Takashi Tsukagoshi, Munetake Momose (Ibaraki Univ.)

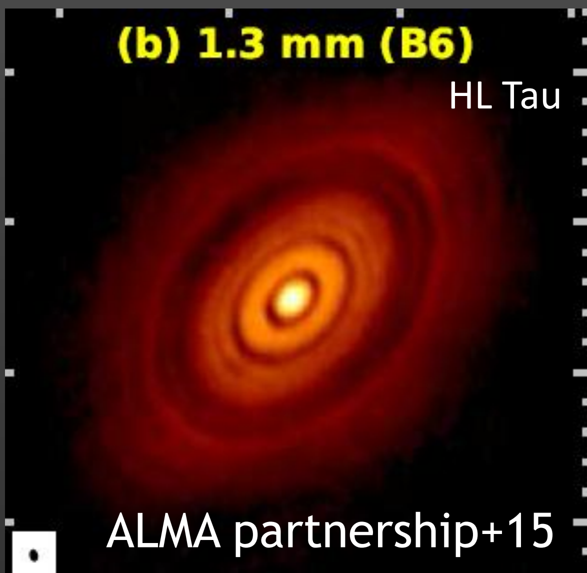
Gap formation induced by a planet

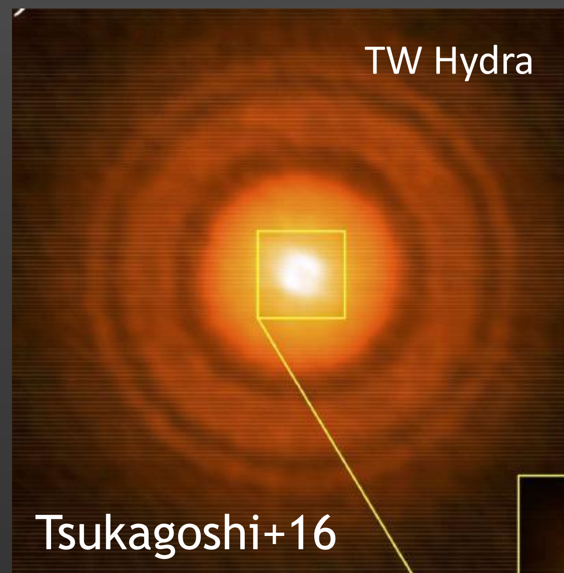


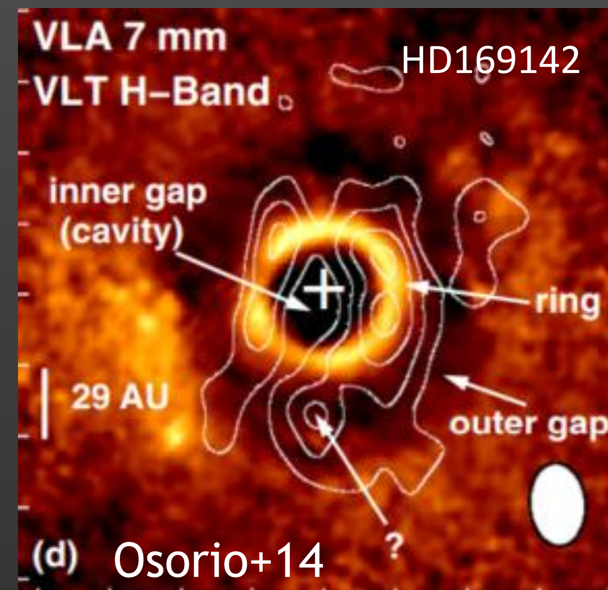
The planet create a gap structure in the disk by disk—planet interaction.

Gaps in protoplanetary disks

Many gaps have been observed on protoplanetary disks



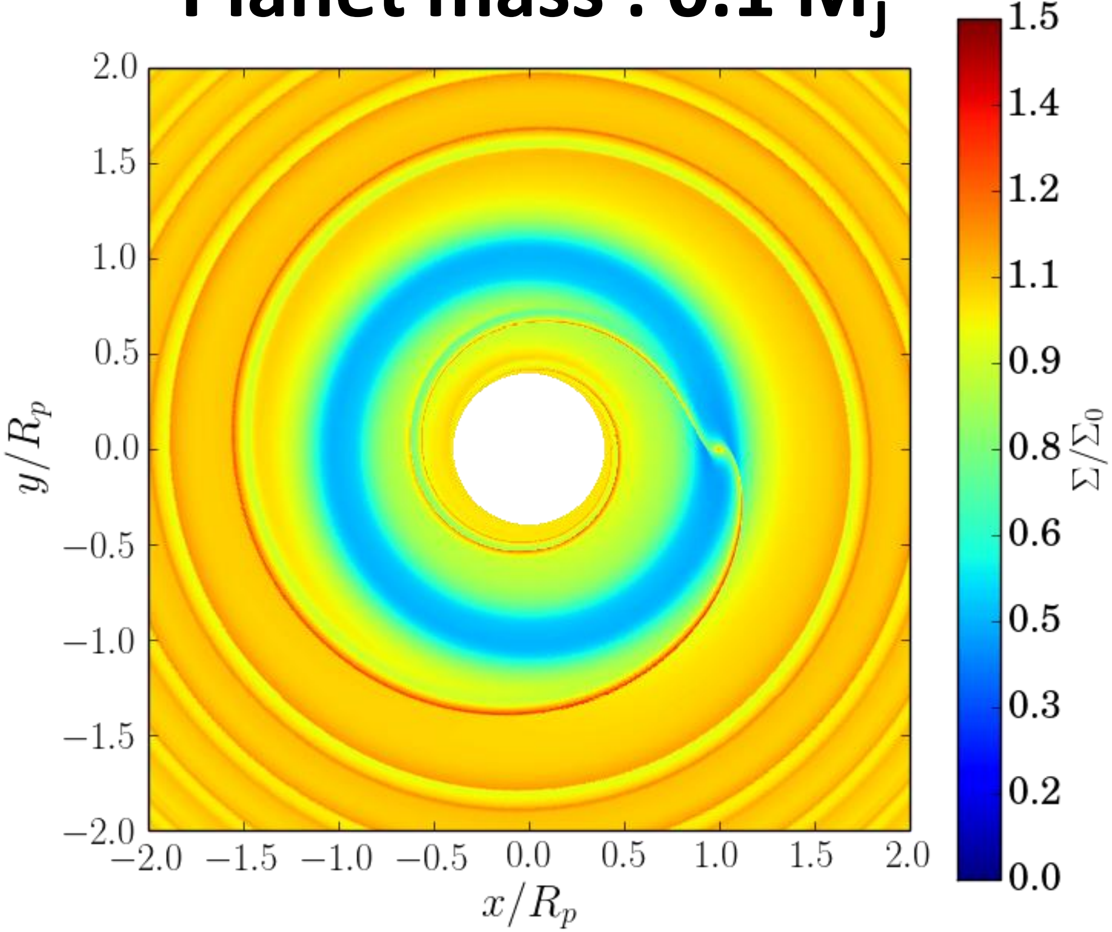




What about planets can we learn from the observation, if these gaps are created by planets?

Planet—induced gaps

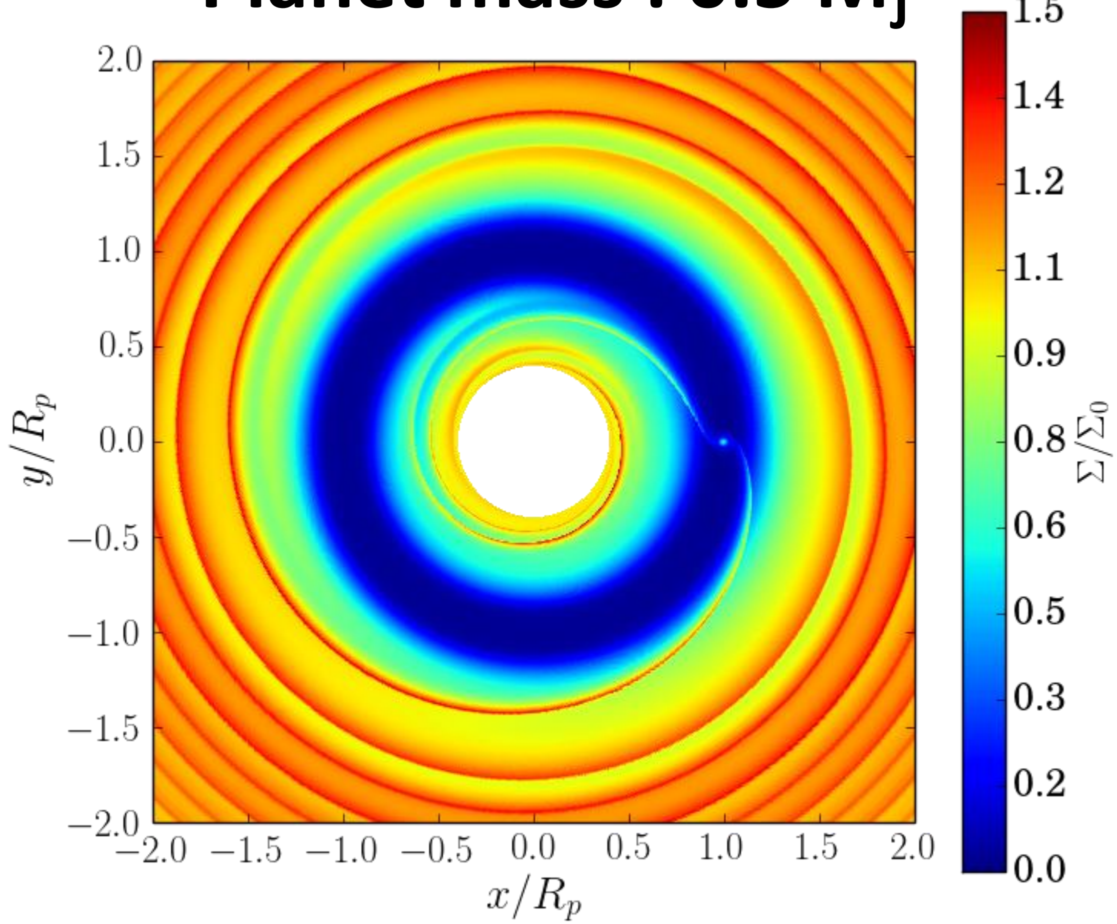
Planet mass : 0.1 M_J



Disk aspect ratio
0.05,
Viscous α
10^{-3}

Planet—induced gaps

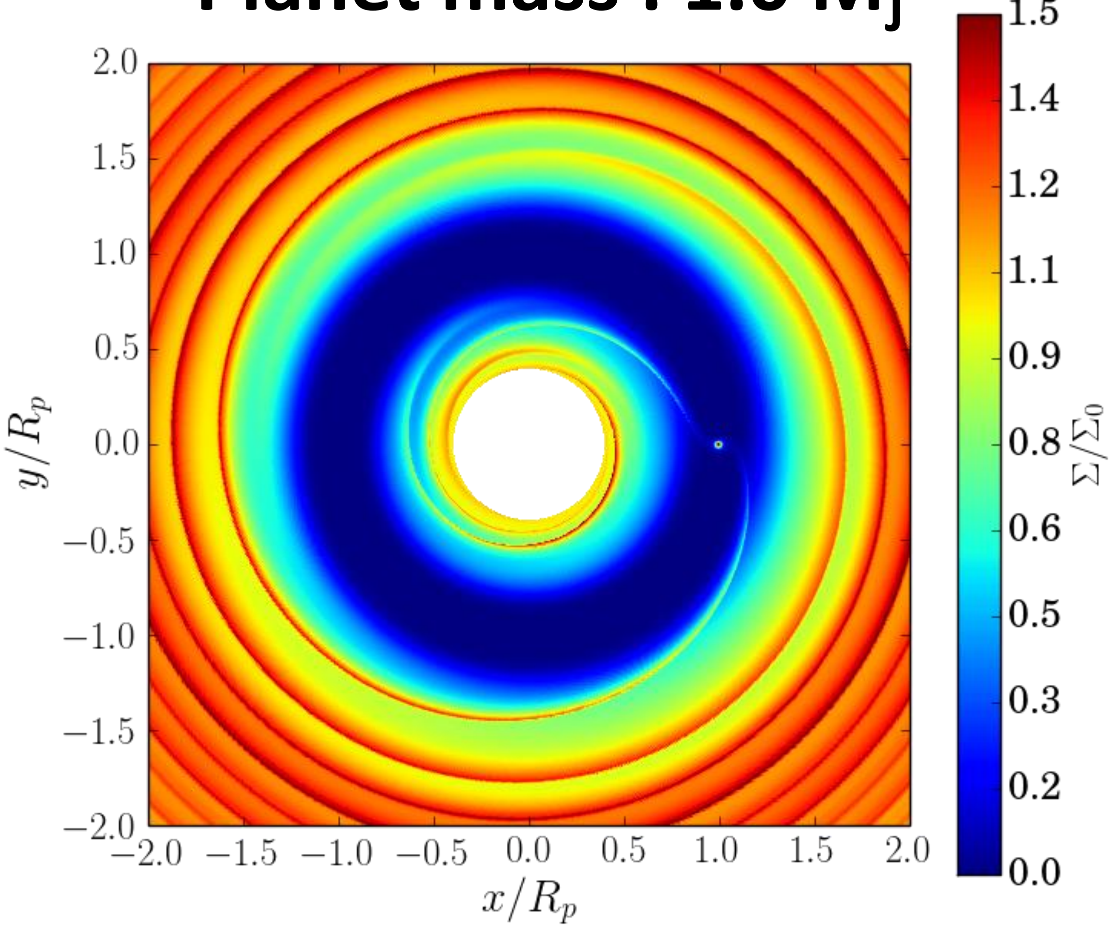
Planet mass : 0.5 M_J



Disk aspect ratio
0.05,
Viscous α
10^{-3}

Planet—induced gaps

Planet mass : 1.0 M_J

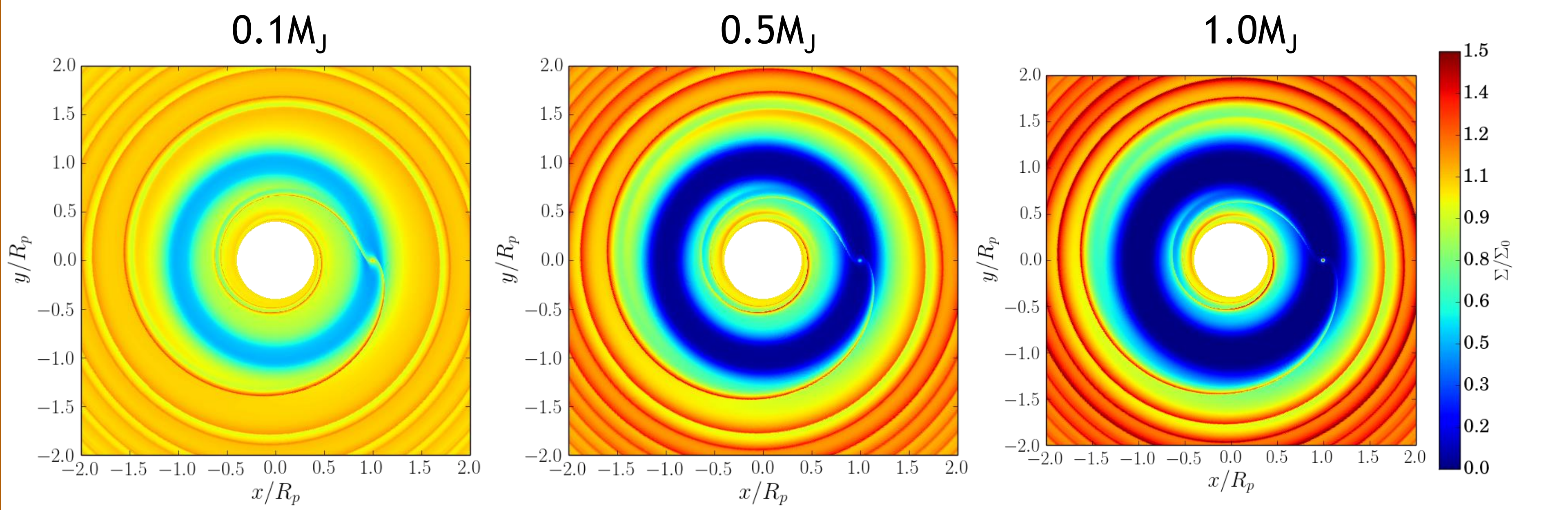


Disk aspect ratio 0.05,
Viscous α 10^{-3}

Planet—induced gaps

Planet mass

small → large



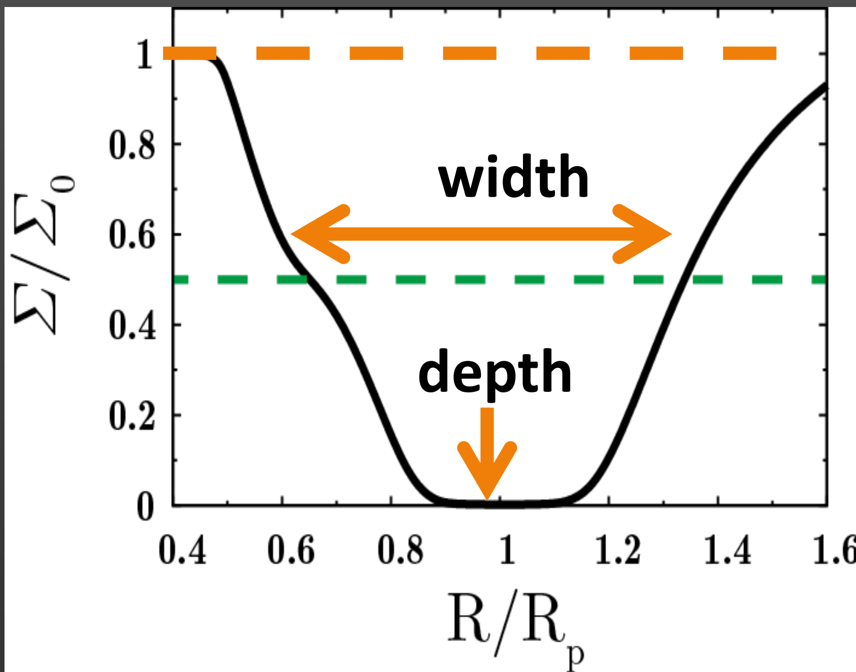
Shallow & narrow → **Gap depth & width** → **deep & wide**

We investigated quantitative relationships between planet mass and gap shape.

Hydrodynamic simulations

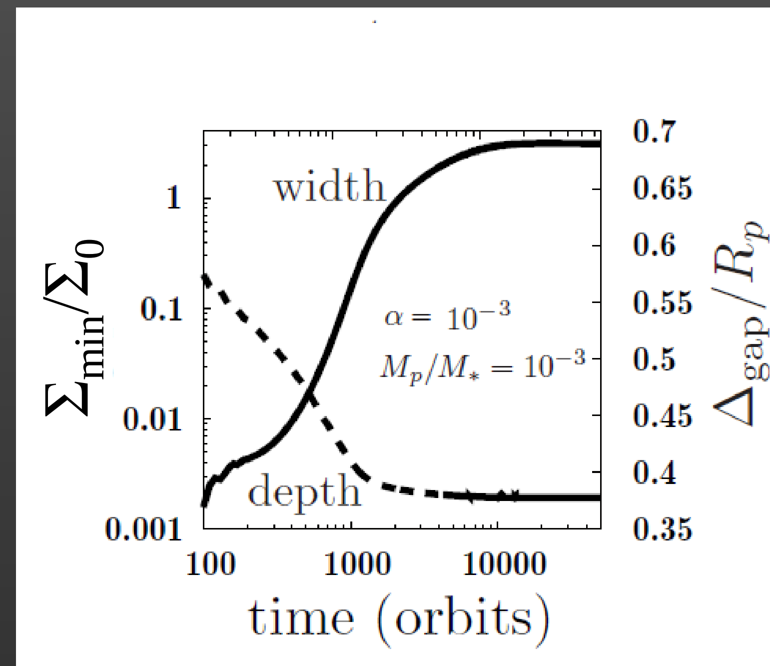
- Two-dimensional simulation using FARGO (Masett 2000)
- Domain: $0.4 < R/R_p < 4$ (Planet is putted on $R=R_p$)
- Resolution: $h_p/22$ (radial), $h_p/16$ (azimuthal)
- No planet mass growing & No migration
- We performed 26 runs varying the disk aspects ratio, the viscosities and the planet masses.

Gap depth and widths



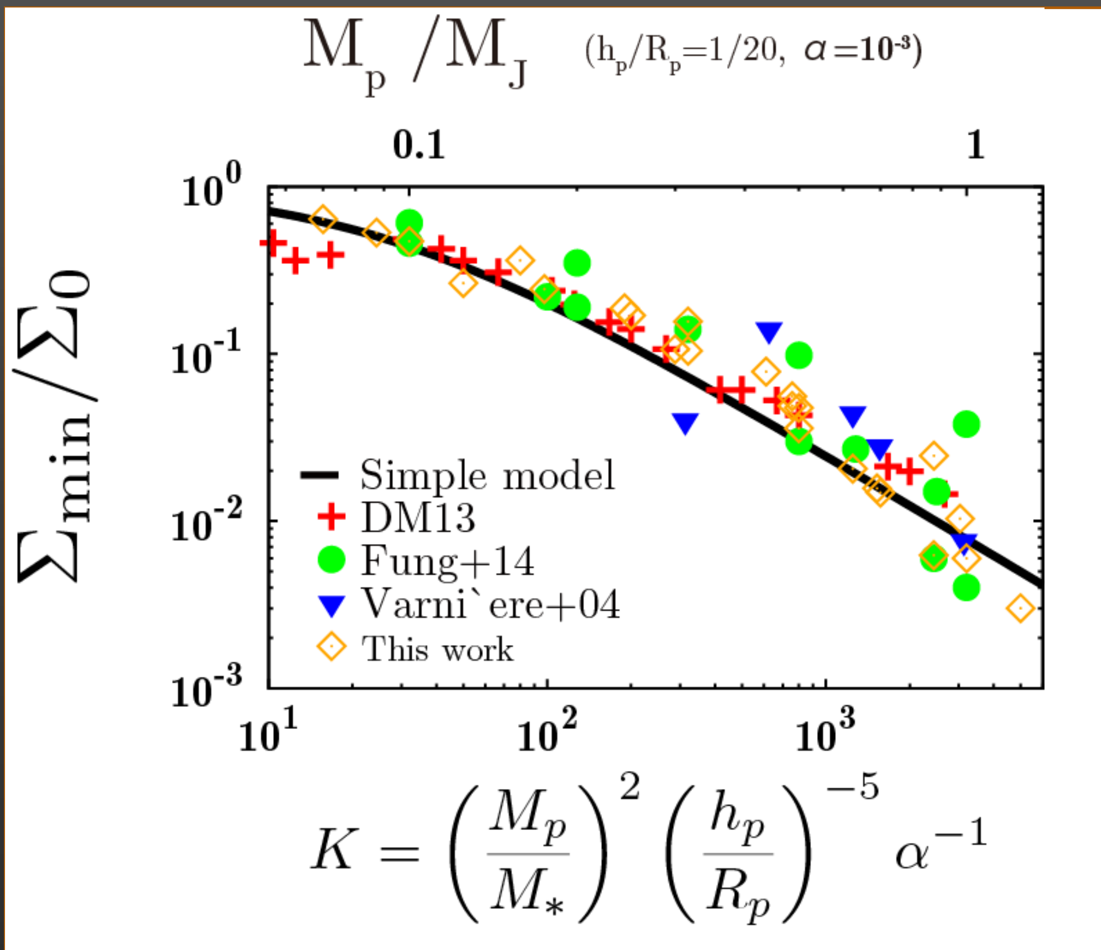
Σ_0

$0.5\Sigma_0$



We calculate evolution until the gap depth and width reach the saturated values (~10000 orbits).

Gap depth and planet mass



Kanagawa+15 MNRAS
Kanagawa+15 ApJL

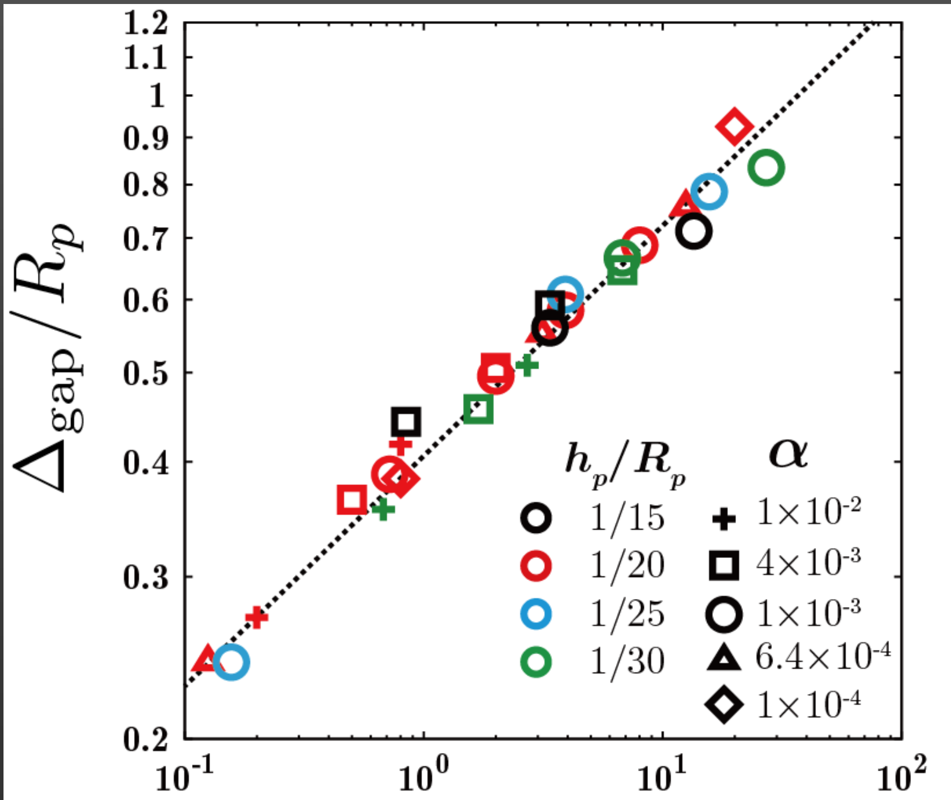
Black line is given by simple model as

$$\frac{\Sigma_{\min}}{\Sigma_0} = \frac{1}{1 + 0.04K}$$

$$\frac{M_{\rm p}}{M_*} = 5 \times 10^{-4} \left(\frac{1}{\Sigma_{\rm p}/\Sigma_0} - 1 \right)^{1/2} \left(\frac{h_{\rm p}}{0.1} \right)^{5/2} \left(\frac{\alpha}{10^{-3}} \right)^{1/2}.$$

Assuming viscosity, a mass of a planet within an observed gap can be estimated from the depth and aspect ratio (temperature).

Gap width and planet mass



$$K' = \left(\frac{M_p}{M_*}\right)^2 \left(\frac{h_p}{R_p}\right)^{-3} \alpha^{-1}$$

$$K' = K \left(\frac{h_p}{R_p}\right)^2$$

Kanagawa+16 PASJ

The gap width is well scaled by

$$\frac{\Delta_{gap}}{R_p} = 0.41 \left(\frac{M_p}{M_*}\right)^{1/2} \left(\frac{h_p}{R_p}\right)^{-3/4} \alpha^{-1/4}$$

$$= 0.41 K'^{1/4}$$

$$\frac{M_p}{M_*} = 2.1 \times 10^{-3} \left(\frac{\Delta_{gap}}{R_p}\right)^2 \left(\frac{h_p}{0.05\ R_p}\right)^{3/2} \left(\frac{\alpha}{10^{-3}}\right)^{1/2}$$

Using this formula, we can estimate a mass of a planet from observed gap width, aspect ratio and assumed viscosity.

Dust filtration

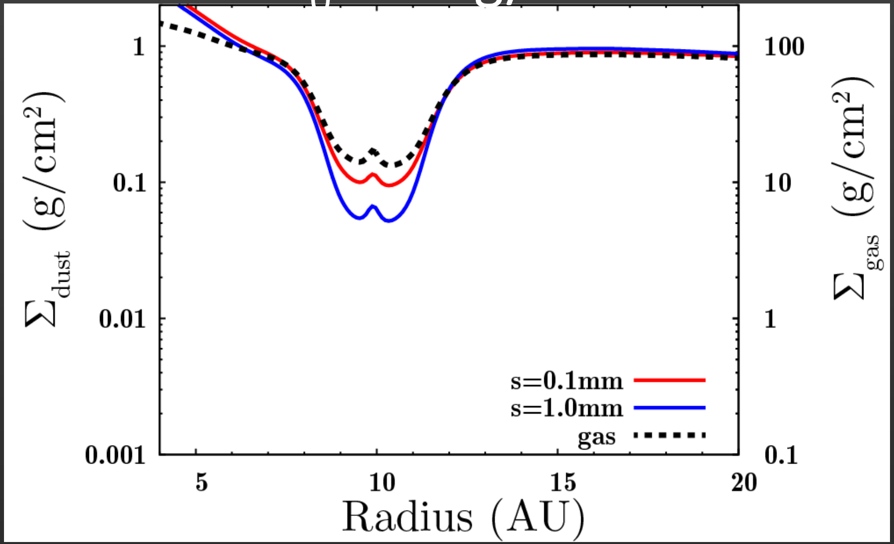
Stopping time

Gas friction

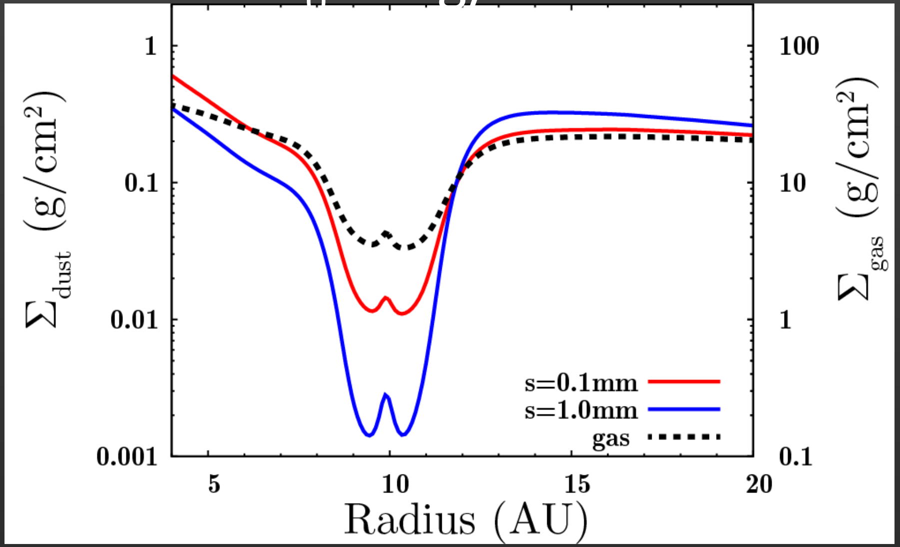
$$\vec{F}_{fric} = -\frac{(\vec{v}_{dust} - \vec{v}_{gas})}{t_s}$$

$$t_s = \frac{\pi s \rho_s}{2\Sigma_{gas}\Omega_K}$$

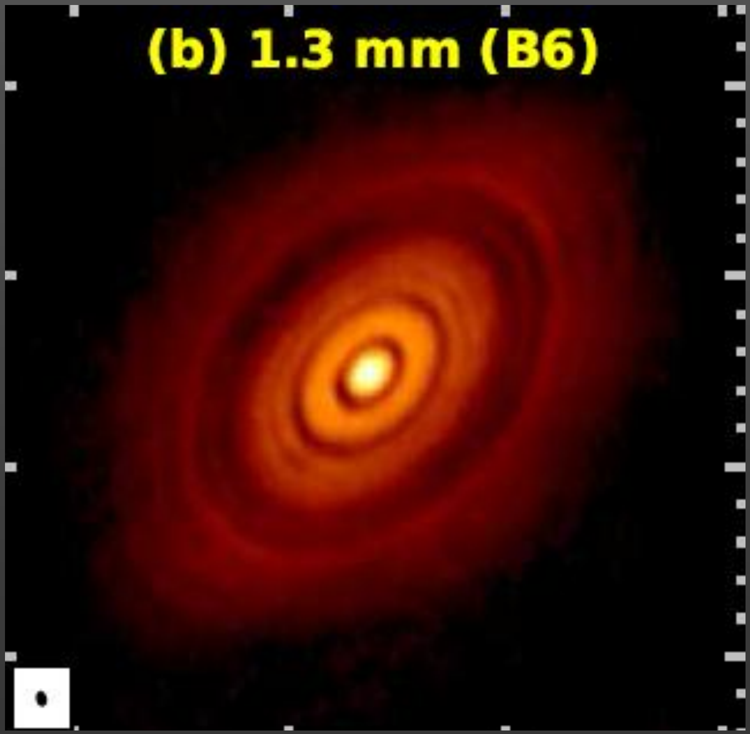
Σ_0=100 g/cm^2



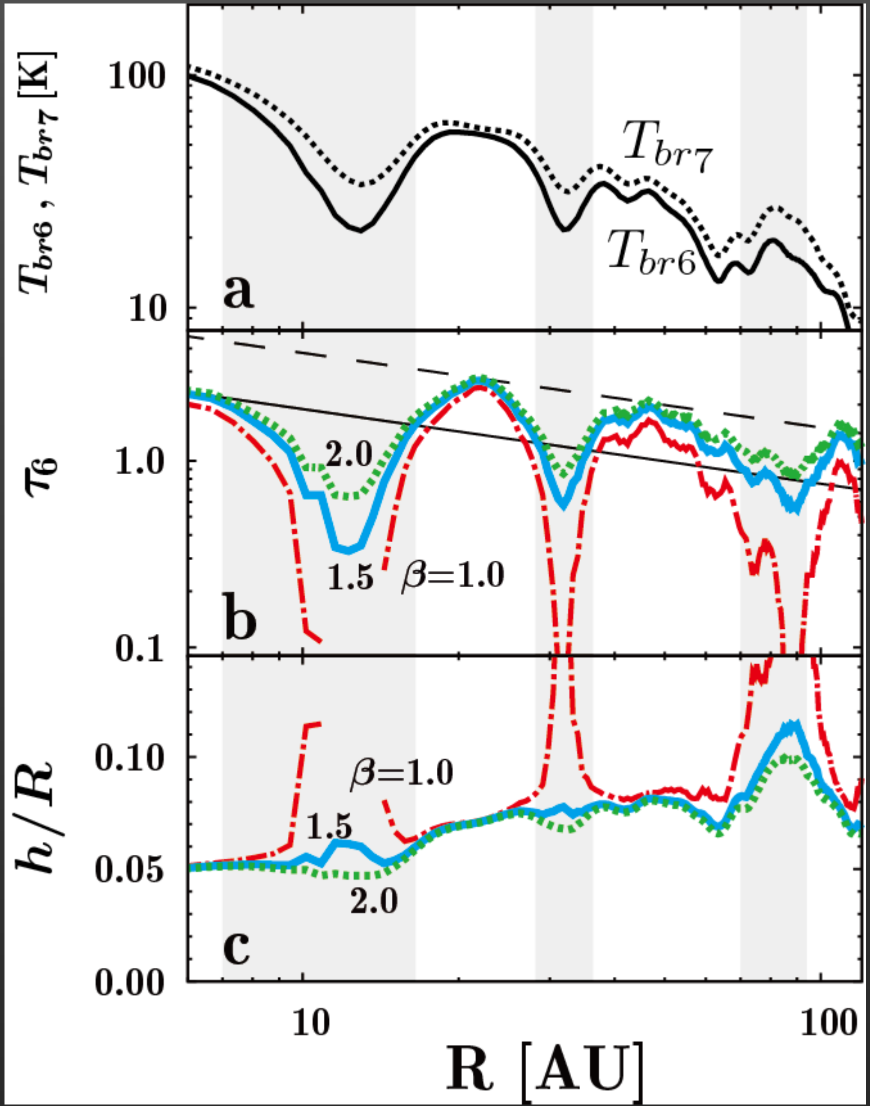
Σ_0=25 g/cm^2



HL Tau



Kanagawa+16 PASJ



$$T_{\mathrm{br6}} = T\left(1 - e^{-\tau_6}\right)$$

$$T_{\mathrm{br7}} = T\left(1 - e^{-\tau_7}\right),$$

$$\tau_7 = \tau_6(\nu_7/\nu_6)^{\beta}$$

HL Tau

1^{st} gap	
R_p	12AU
Δ_{gap}	9.5AU
Σ_{min}/Σ_0	> 0.1
M_p (from width)	**1.4 M_J**
M_p (from depth)	**> 0.3 M_J**
2^{nd} gap	
R_p	30AU
Δ_{gap}	7.5AU
Σ_{min}/Σ_0	~ 0.3
M_p (from width)	**0.2 M_J**
M_p (from depth)	**0.3 M_J**
3^{rd} gap	
R_p	80AU
Δ_{gap}	24AU
Σ_{min}/Σ_0	~ 0.3
M_p (from width)	**0.5 M_J**
M_p (from depth)	**0.7 M_J**

Kanagawa+16 PASJ

M_{disk} ~ $0.1M_{sun}$ (Kwon et al. 2011)

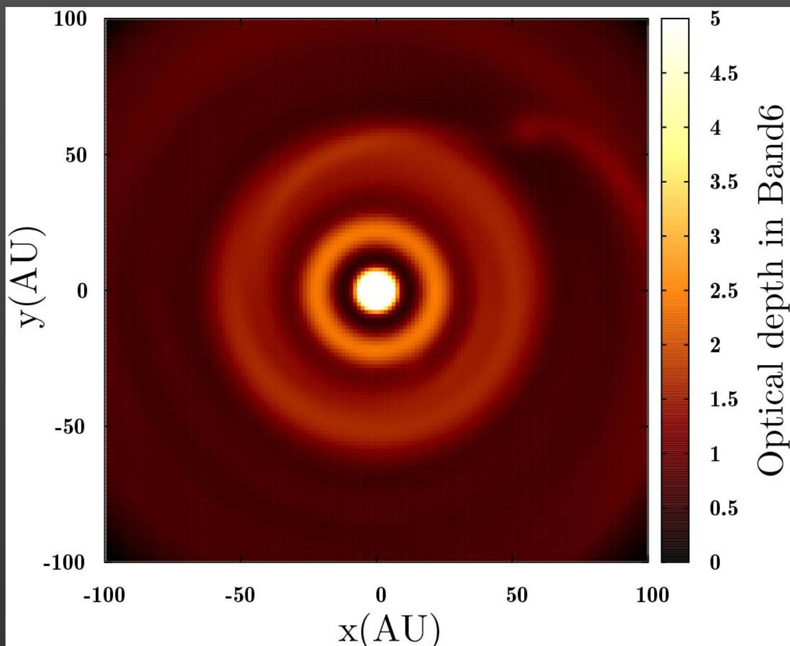
Assumption:
Dust is well—coupled to disk gas

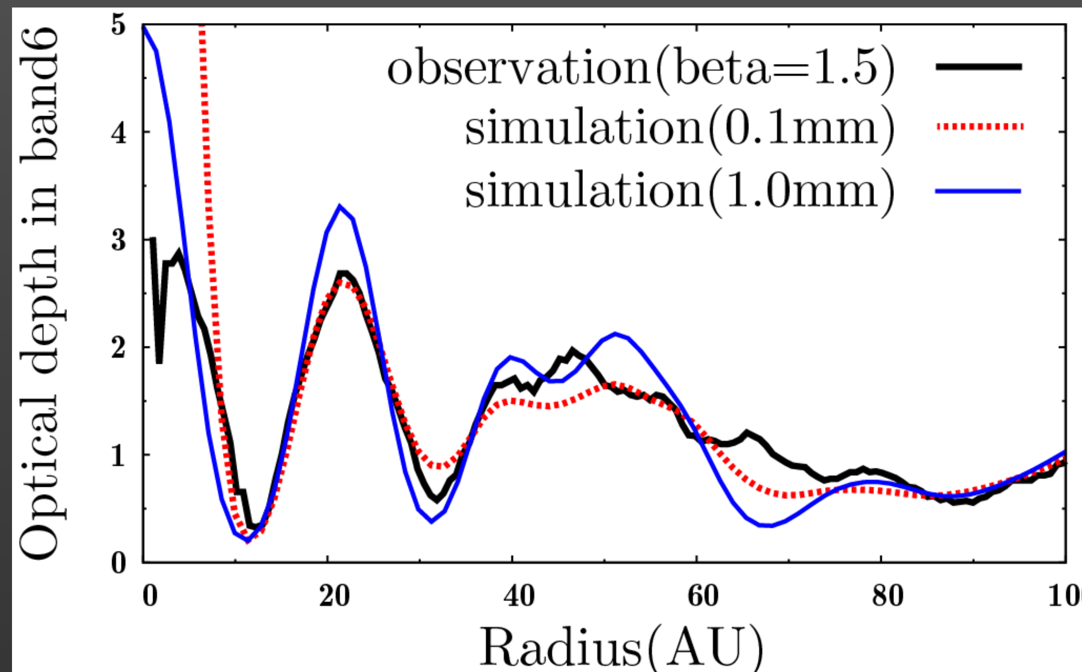
We found three planets:
If $M_{star} = 1M_{sun}$ ($0.55M_{sun}$)
- 1.4 M_J($0.77M_J$) at 10AU
- 0.2 M_J($0.11M_J$) at 30AU
- 0.5 M_J($0.28M_J$) at 80 AU

($\alpha=10^{-3}$)

HL Tau

Results of two—fluid hydrodynamic simulations convolved with Gaussian beam





Planet masses: **1.4** M_J (12AU), **0.2**M_J(30AU) and **0.5**M_J(80AU)

The distribution of 0.1 mm sized—particle is quite similar to that of gas.
This result is consistent with Jin et al. (2016), Dong et al. (2015), though if the gas disk is more less massive, the planet mass can be smaller (Dipierro+15, Rosotti+16).

Summary

- We have investigated a relationship between planets and gaps by using hydrodynamic simulations.
- We have found the quantitative relationships between the planet mass and gap width and depth, which are useful to estimate the mass of planet within observed gaps.
- Applying our formula, we estimated masses of planets within observed gaps of HL Tau disk as $1.4M_J$ (12AU), $0.2M_J$(30AU), $0.5M_J$(80AU).